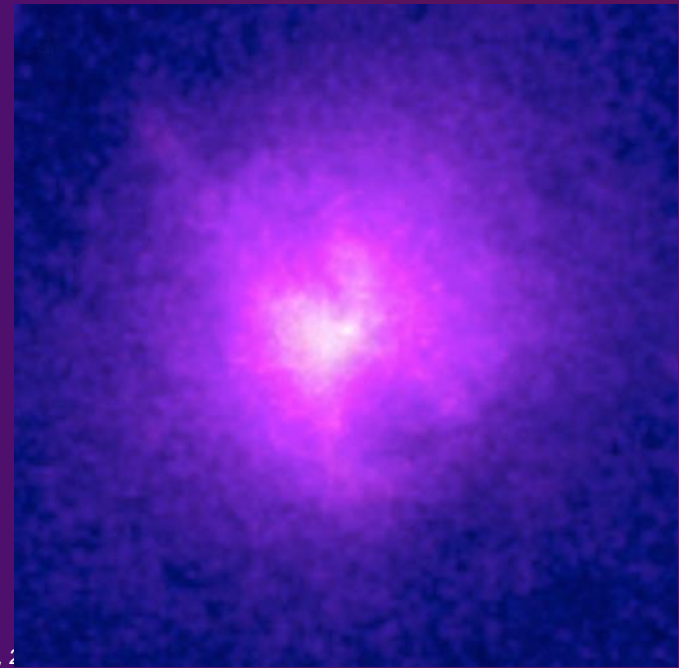


# Cold Probes of the Hot Universe

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# Opening remarks

- It's an pleasure to have the opportunity to visit your remarkable city. It's an honor to be here this morning.
- I apologize for subjecting you to a lecture in English. I will try not to speak to quickly.
  - but sometimes I get too excited! So, please forgive me if that happens!

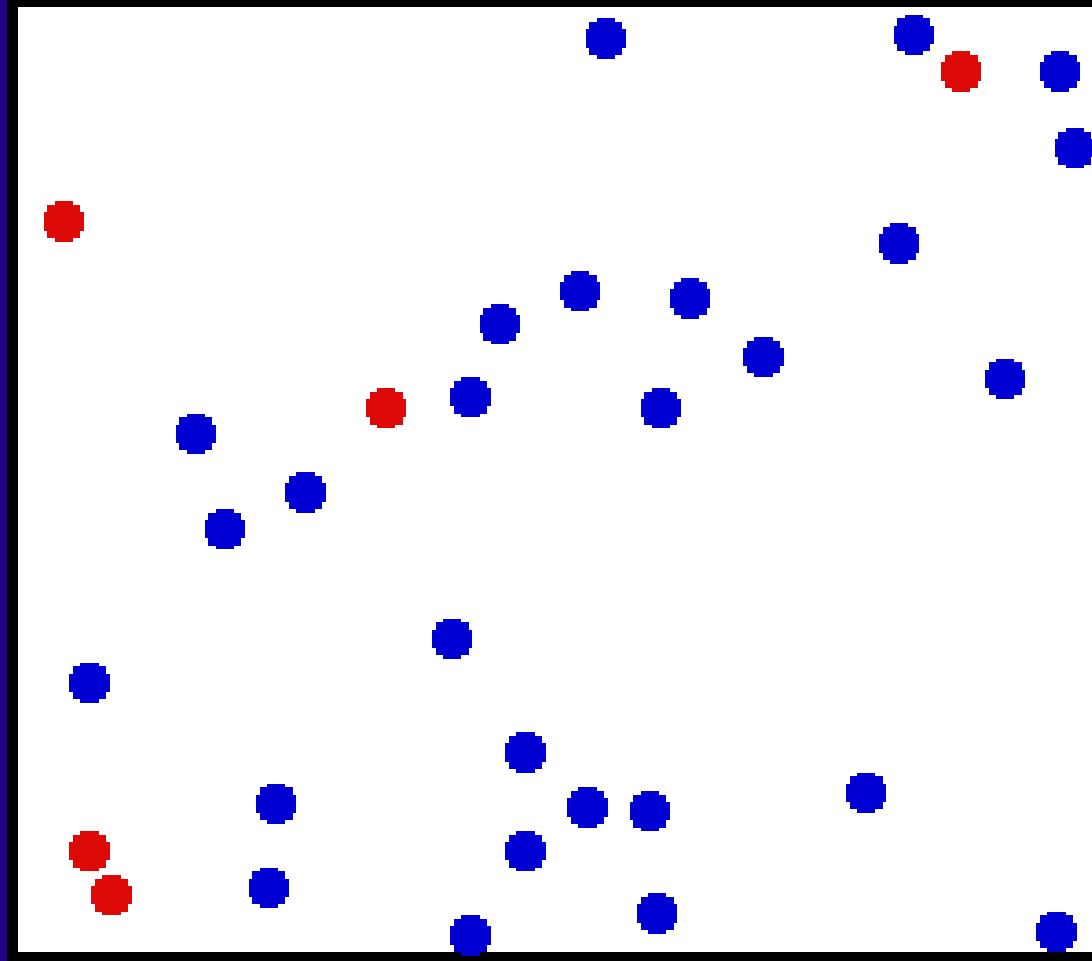
# Cold Probes of the Hot Universe: The Storyline

- This is a story about energy
  - about temperature
  - about the very cold and the very hot
- It is a story about the very small
  - and the enormous
- I invite you to hold these extremes in you mind
  - AT THE SAME TIME!
- Let's go!

# Where should I start?

- with the cold probes?
- with the hot Universe?
- Let's start with TEMPERATURE.
- Each of us has an innate understanding of “temperature”. The air is hot today. The ice water is cold. But what does “temperature” really mean?
- You probably have some understanding that temperature relates to heat, and that heat is energy
  - and that temperature indicates the average energy of a particle in the system it describes
    - like the kinetic energy of a molecule in that hot air
  - But it's not only the average energy that is important. but also the distribution of the energies. If the distribution is not in the most probable configuration, then the concept of a temperature of the system has no meaning.

# Temperature



By Greg L at the English language Wikipedia, CC BY-SA 3.0,  
<https://commons.wikimedia.org/w/index.php?curid=1325234>

# Temperature scale (Kelvin)

- 0 K – absolute zero – lowest energy state
- 4 K – helium is liquid (at atmospheric pressure)
- 77 K – nitrogen is liquid (at atmospheric pressure)
- 273 K – water freezes
- 300 K – summer day (27 ° C)
- 1000 K – glows red (to human eyes)\*
- 6000 K – glows white (to human eyes)\*
- 10,000 K – glows blue (to human eyes)\*
- 1,000,000 to 100,000,000 K – **glows in X-rays!**\*

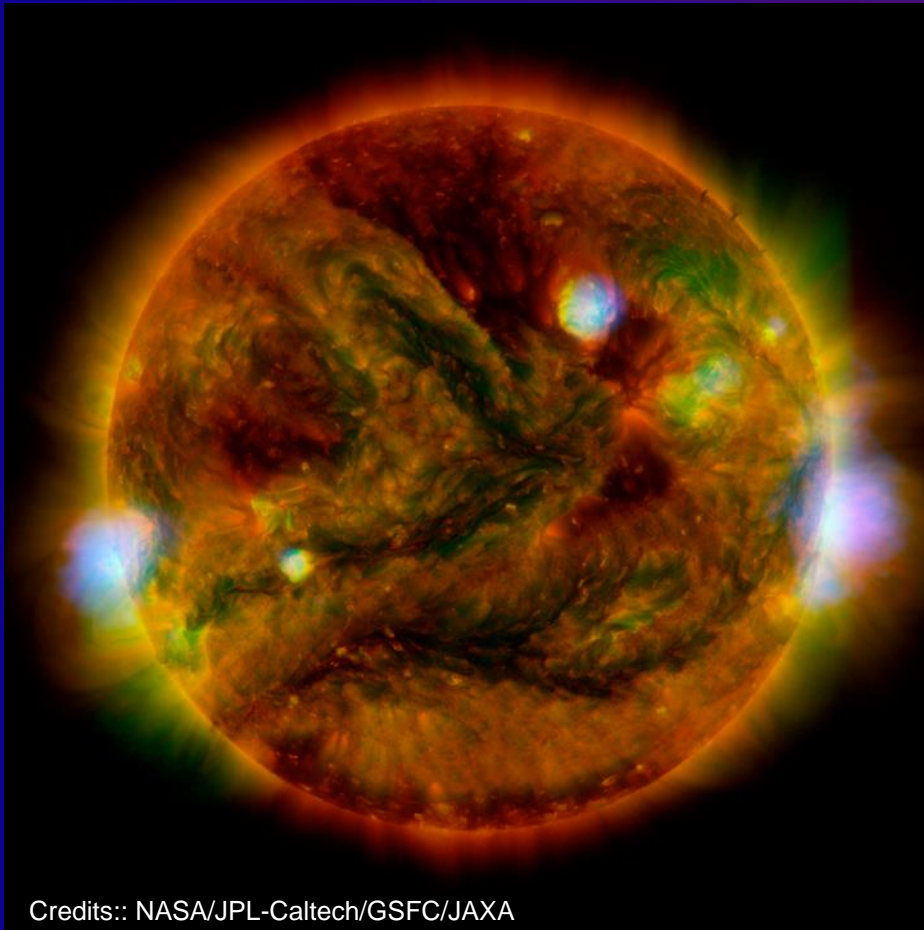
\* What is this? This is thermal radiation. When material is in thermal equilibrium with surrounding electromagnetic radiation, that radiation has a spectrum that is characteristic of the temperature.



# To see the hot Universe, we need X-ray vision!

- 1 - 100 million degrees! What in the Universe is that HOT?

The coronae of stars! The sun is an X-ray source! X-rays from the sun were first detected in 1949.



In this image, data from NASA's NuSTAR and SDO satellites and JAXA's Hinode satellite acquired on April 29, 2015 are combined. The high-energy X-rays seen by NuSTAR are shown in blue, while green represents lower-energy X-rays from Hinode's X-ray Telescope instrument. The yellow and red colors show ultraviolet light from NASA's Solar Dynamics Observatory. The blue regions produce the highest energy X-rays, and correspond to over 3 million Kelvin. The average corona temperature is 1 million Kelvin.

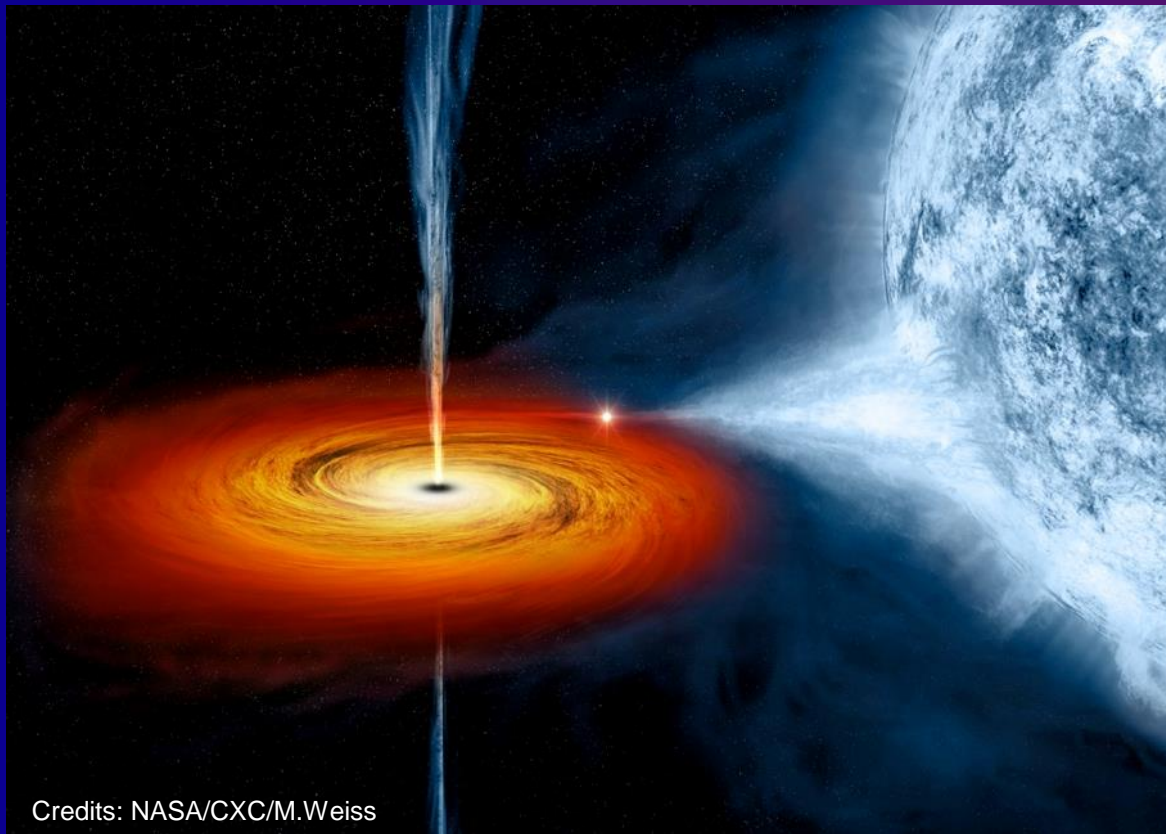
Credits:: NASA/JPL-Caltech/GSFC/JAXA



# To see the hot Universe, we need X-ray vision!

- 1 - 100 million degrees! What in the Universe is that HOT?

Matter falling into black holes and neutron stars! As the matter falls in, the density increases and the gas gets hot. X-rays from beyond the solar system were first detected in 1962.



Credits: NASA/CXC/M.Weiss

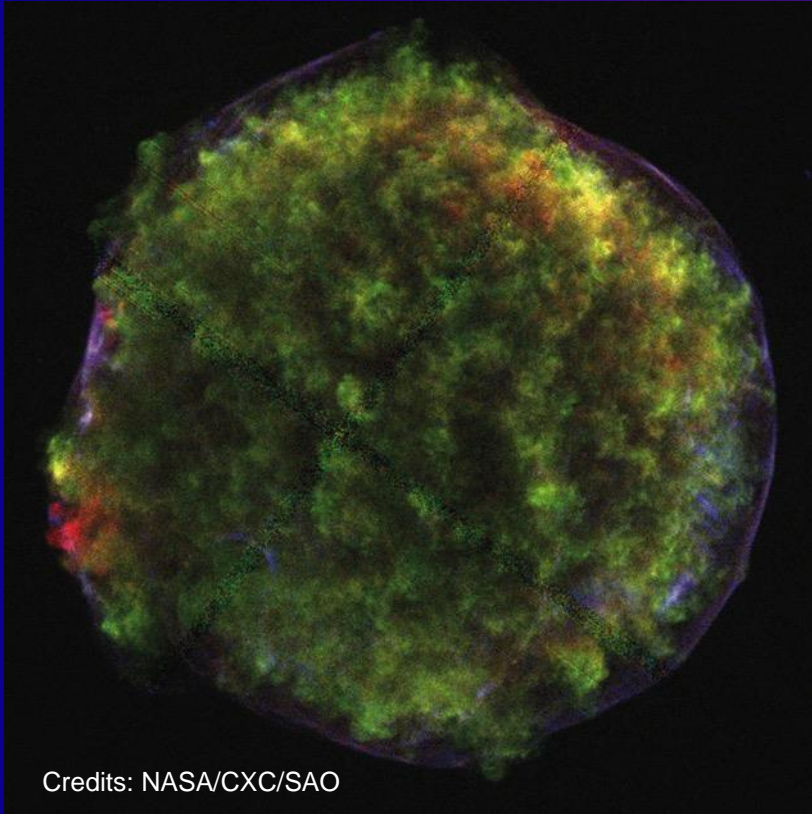
This image is an artist's rendering of matter from a normal star (blue) spiraling into a neutron star. (A neutron star is a collapsed star that is very small but very dense.) X-rays are produced by the matter around the neutron star.



# To see the hot Universe, we need X-ray vision!

- 1 - 100 million degrees! What in the Universe is that HOT?

Remnants of exploded stars!



# To see the hot Universe, we need X-ray vision!

- 1 - 100 million degrees! What in the Universe is that HOT?

Winds from star-forming galaxies (produced by exploding stars)!



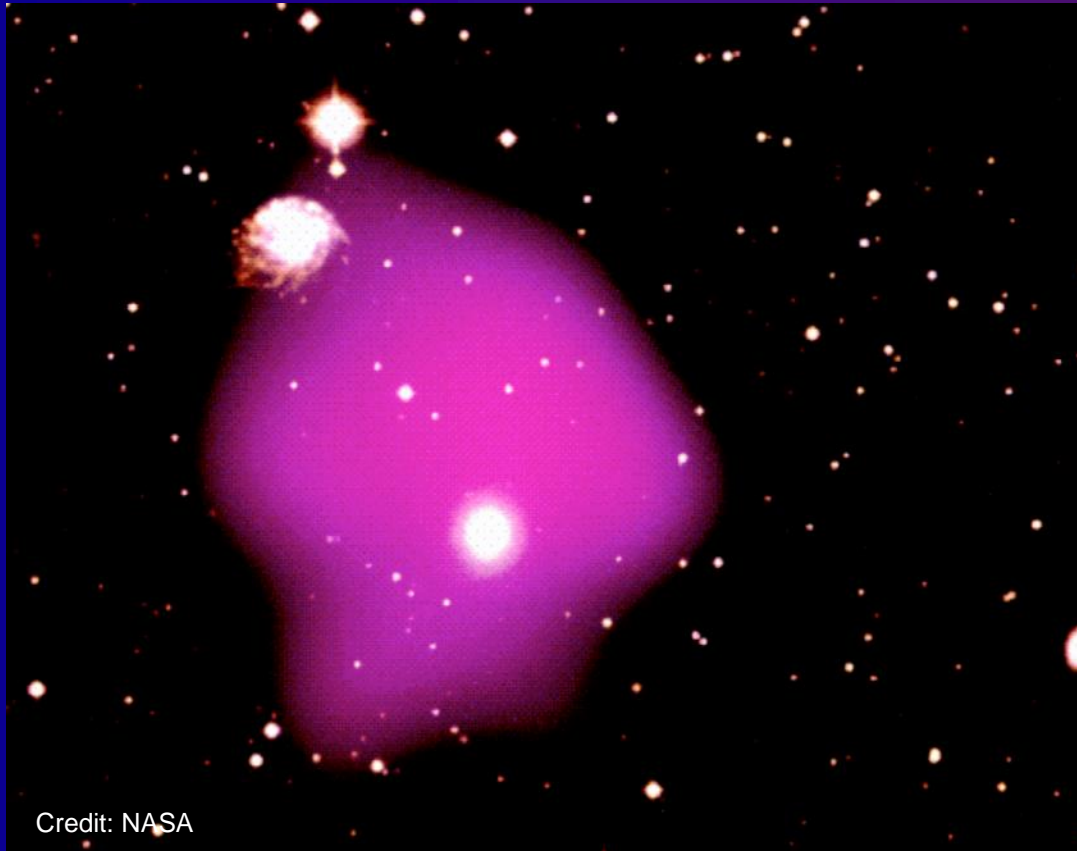
Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbrach

In this image, data from NASA's Spitzer, Hubble, and Chandra satellites are combined. Optical light from stars (yellow-green/Hubble) shows the disk of an apparently normal galaxy. Another Hubble observation designed to image 10,000 K hydrogen gas (orange) reveals matter blasting out of the galaxy. The Spitzer infrared image (red) shows that cool gas and dust are also being ejected. Chandra's X-ray image (blue) reveals gas that has been heated to millions of degrees by the violent outflow.

# To see the hot Universe, we need X-ray vision!

- 1 - 100 million degrees! What in the Universe is that HOT?

Hot gas trapped by the gravity of matter we can't see!



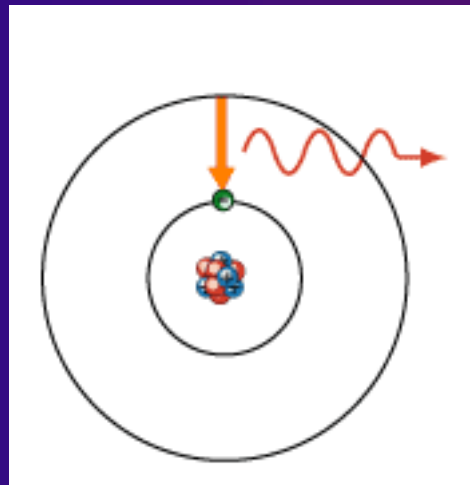
Credit: NASA

In this image, data from the German ROSAT satellite is combined with an optical image of the same field of view of a cluster of galaxies. X-ray emission is shown in pink.

# What else in the Universe makes x-rays?

- Electrons accelerated in strong magnetic fields ( $\sim 10^{12} - 10^{14}$  Gauss).
- Electronic transitions in partially ionized atoms of atomic number greater than or equal to 4 (beryllium) produce X-rays at characteristic energies. \*
  - collisionally ionized (thus **HOT**) or photo-ionized

\* What is this? Atoms and ions consist of nuclear (protons and neutrons) and electrons that are only allowed to have certain particular energies, but only two electrons can occupy each energy level. If an electron absorbs energy, it can move to a higher energy level, and to move an available lower energy level it needs to lose energy.



OK, X-rays show us a hot and energetic Universe.  
Why do we care?

There's a lot of hot stuff out there!  
93% of the “ordinary” matter in the  
Universe radiates x-rays. Much of it  
cannot be studied without X-rays!

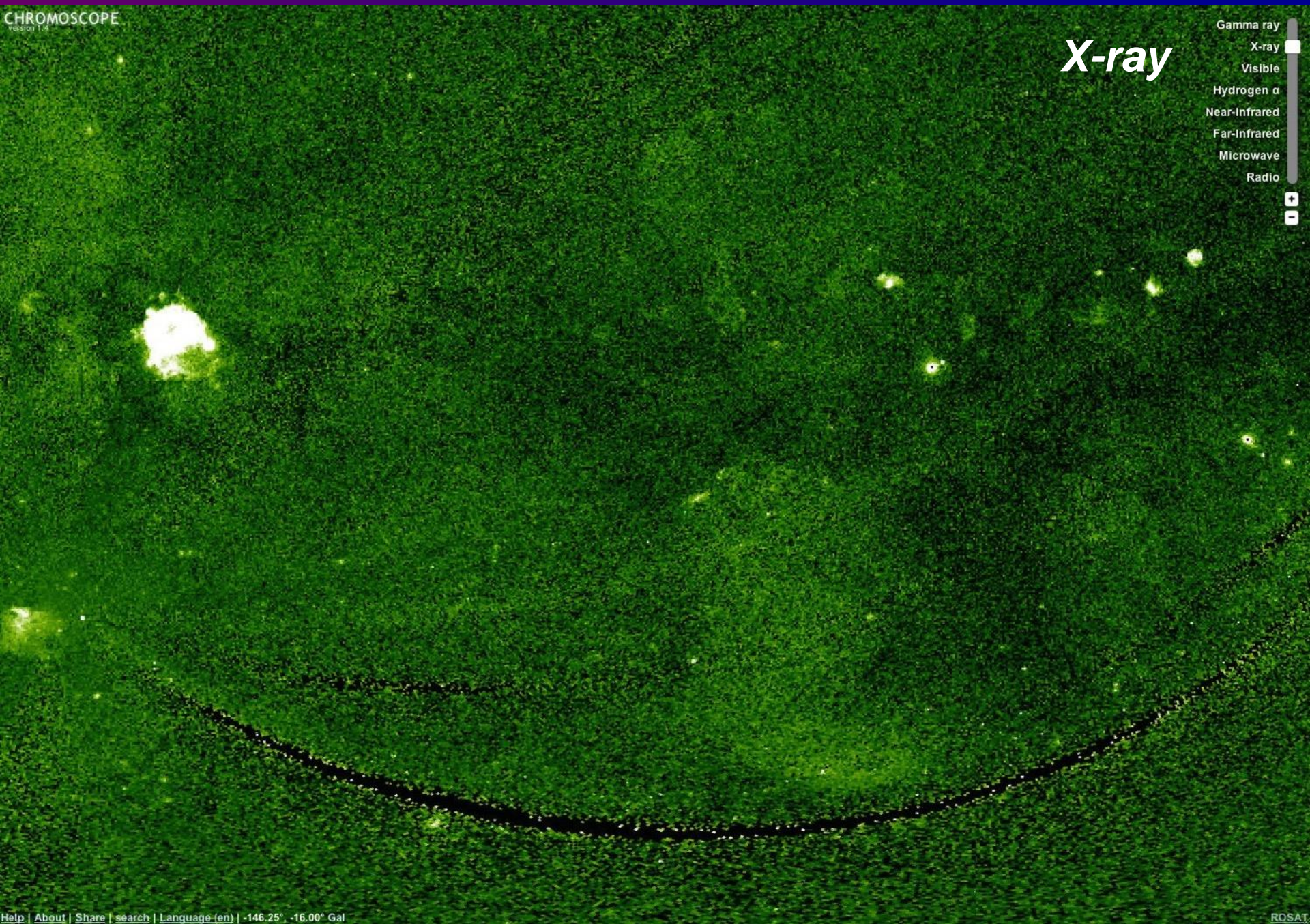
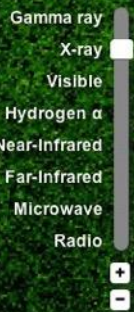


# Optical





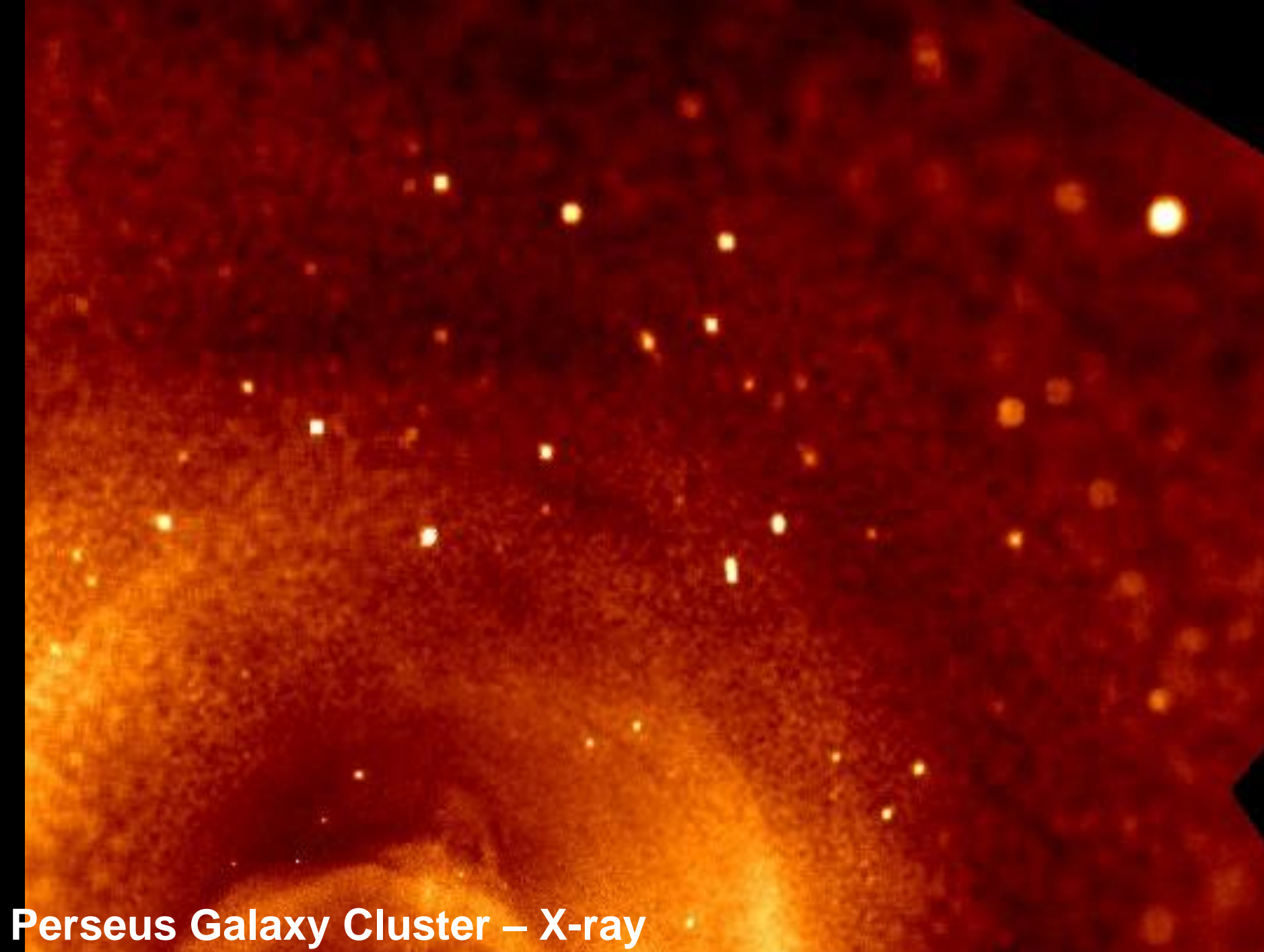
*X-ray*





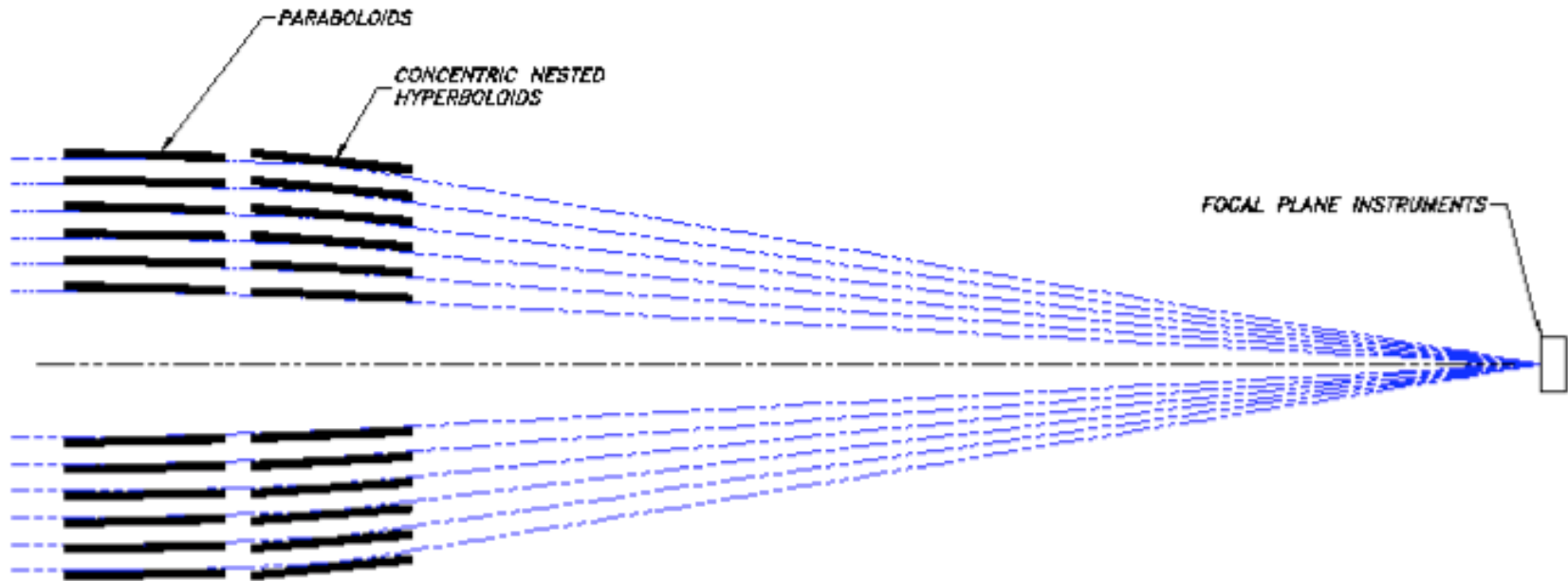


**Perseus Galaxy Cluster - visible**



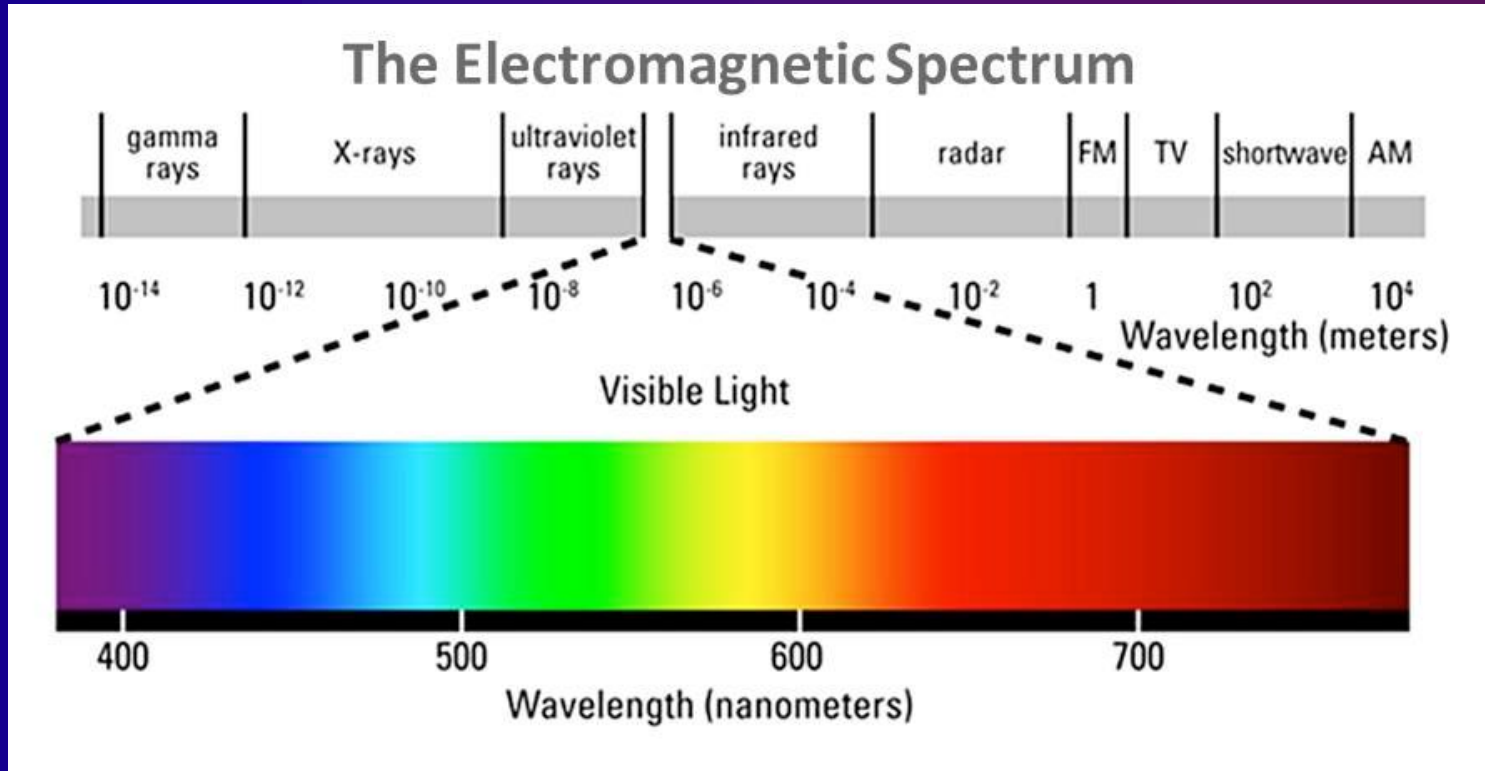
**Perseus Galaxy Cluster – X-ray**

# So many pretty pictures, but how are we focussing X-rays?



- We focus x-rays, not with lenses, but with mirrors, using grazing incidence scattering.
- And X-ray telescopes need to be on satellites, because X-rays don't penetrate Earth's atmosphere.

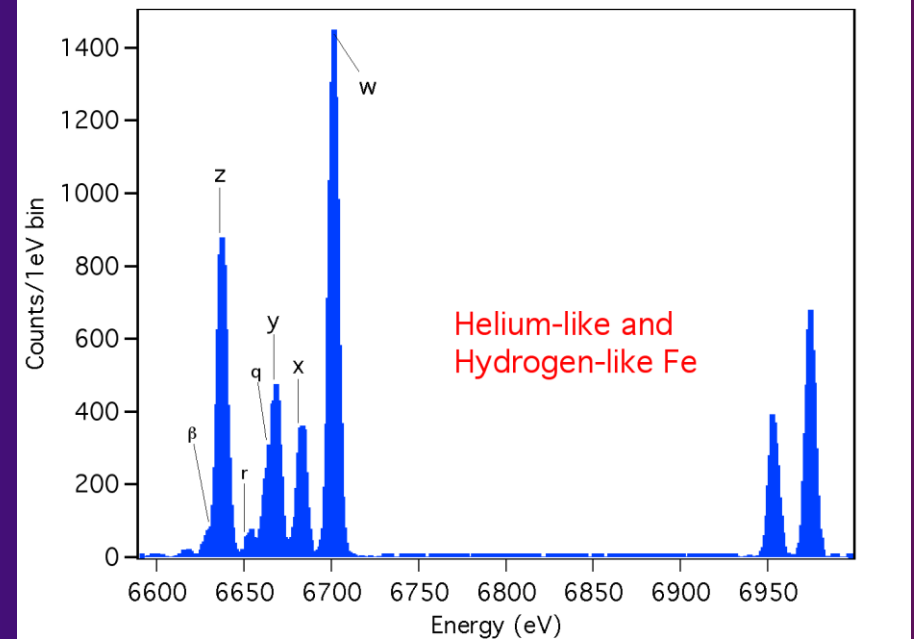
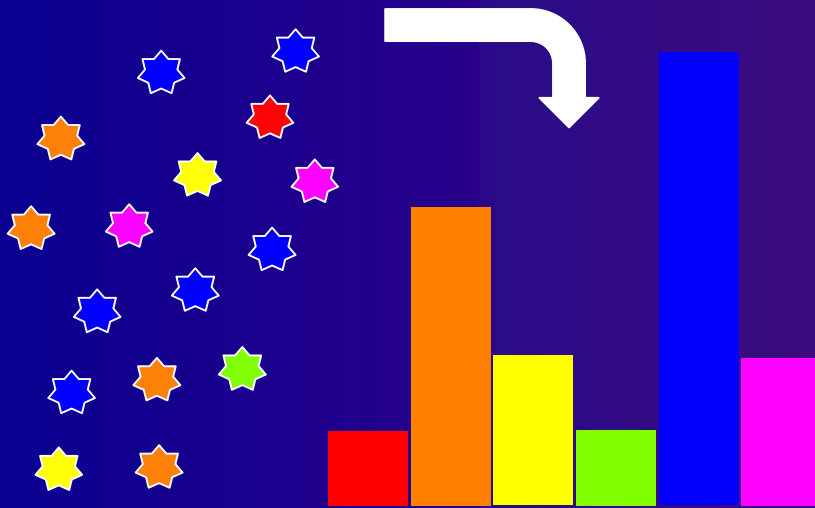
So many pretty pictures, but X-ray spectra tell us so much more!



- X-rays have “colors”, too! We need X-ray eyes with color vision.
- Measurement of characteristic x-ray emission lines tells us what atoms compose the gas and the temperature and density.
- Shifts and broadening of these characteristic energies tell us how the gas is moving around.



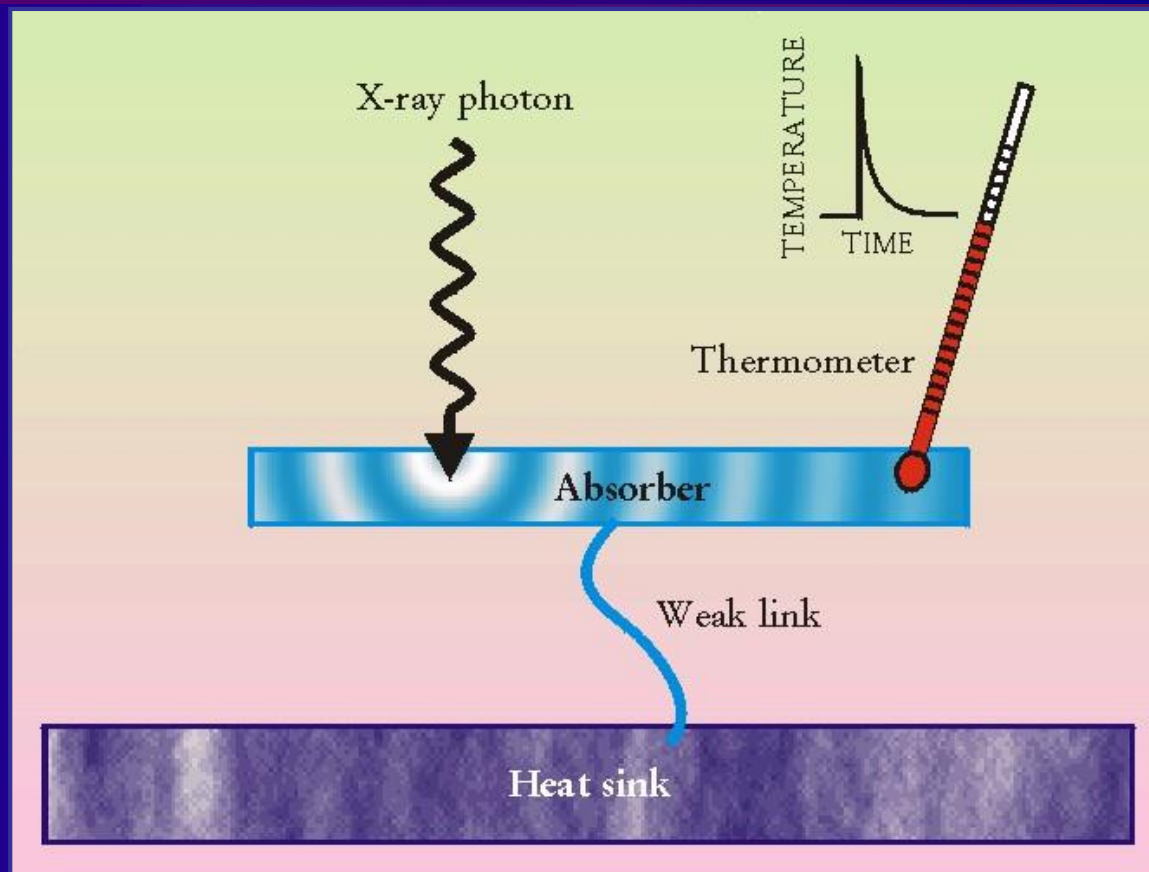
# X-ray spectroscopy



- A spectrum is just a bargraph that displays how many photons in a particular energy range (color) were measured.
- We can determine energy dispersively (like a prism) or by directly measuring the energy of individual photons.
  - For extended sources, dispersive spectrometers mix spectral and spatial information.
  - Direct measurement of energy does not have this problem.
- High resolution allows us to separate spectral features and measure their shapes.

# How can we measure energy?

- In most X-ray detectors, the X-ray produce ionization, and the burst of excited electrons is the signal.
- For the highest energy resolution, we want to make a calorimetric measurement, in which all the energy of an X-ray photon heats the sensor, and we measure the resulting temperature change.
- Even though X-rays come from some of the hottest and most energetic places in the Universe, individual X-ray photons don't have very much energy. In order to measure them with high resolution we need:
  - a very low operating temperature, so that thermal noise is low
  - materials that have low heat capacity, which means a bigger temperature change can come from a small amount of energy
  - a sensitive thermometer, so a large signal can come from a small change in temperature
- We need detectors that are colder than 0.1 K to study the hotter than 1,000,000 K Universe!

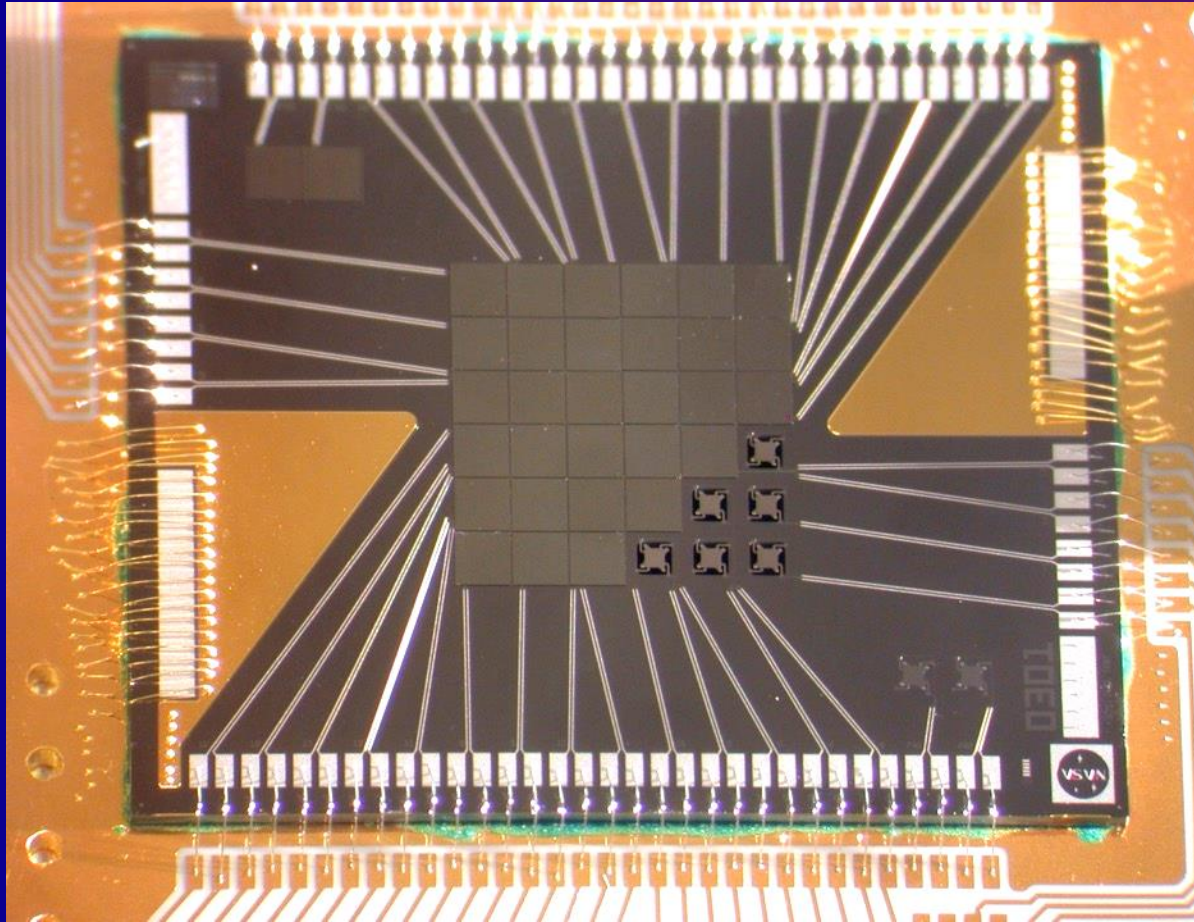


- X-ray photon is absorbed by an electron in the absorber.
- The electron scatters, giving its energy to other electrons and vibrations in the absorber.
- Then the thermometer can measure the temperature change.
- The sensor then cools off.



# Arrays

- One microcalorimeter isn't very useful. We want spectroscopy AND we want imaging!



***6 x 6 Hitomi/SXS  
calorimeter array under  
assembly***

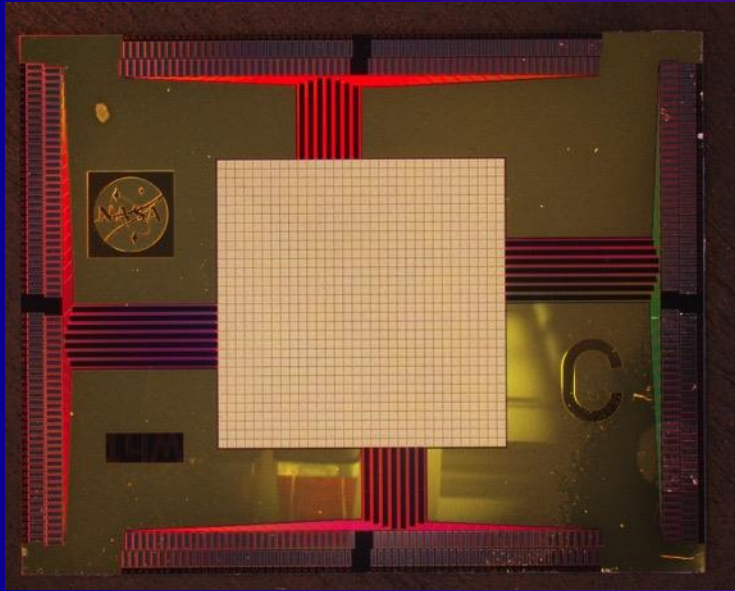
***Si thermistor***

***HgTe absorbers  
(~ 10 microns thick)  
attached manually***

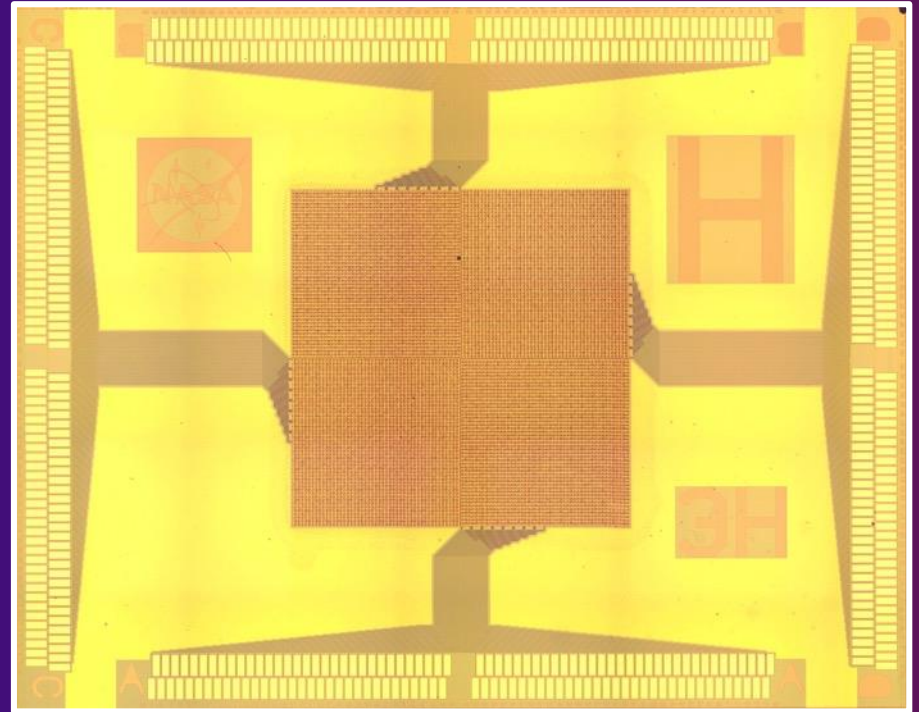
***Pixel size: 832 x 832  
microns  
(30 x 30 arcsec)***

# Arrays with more pixels

- Silicon thermistor arrays are impractical for much larger arrays
- Future arrays using superconducting or magnetic thermometers, with the absorber attached as part of the detector microfabrication, are well under development.

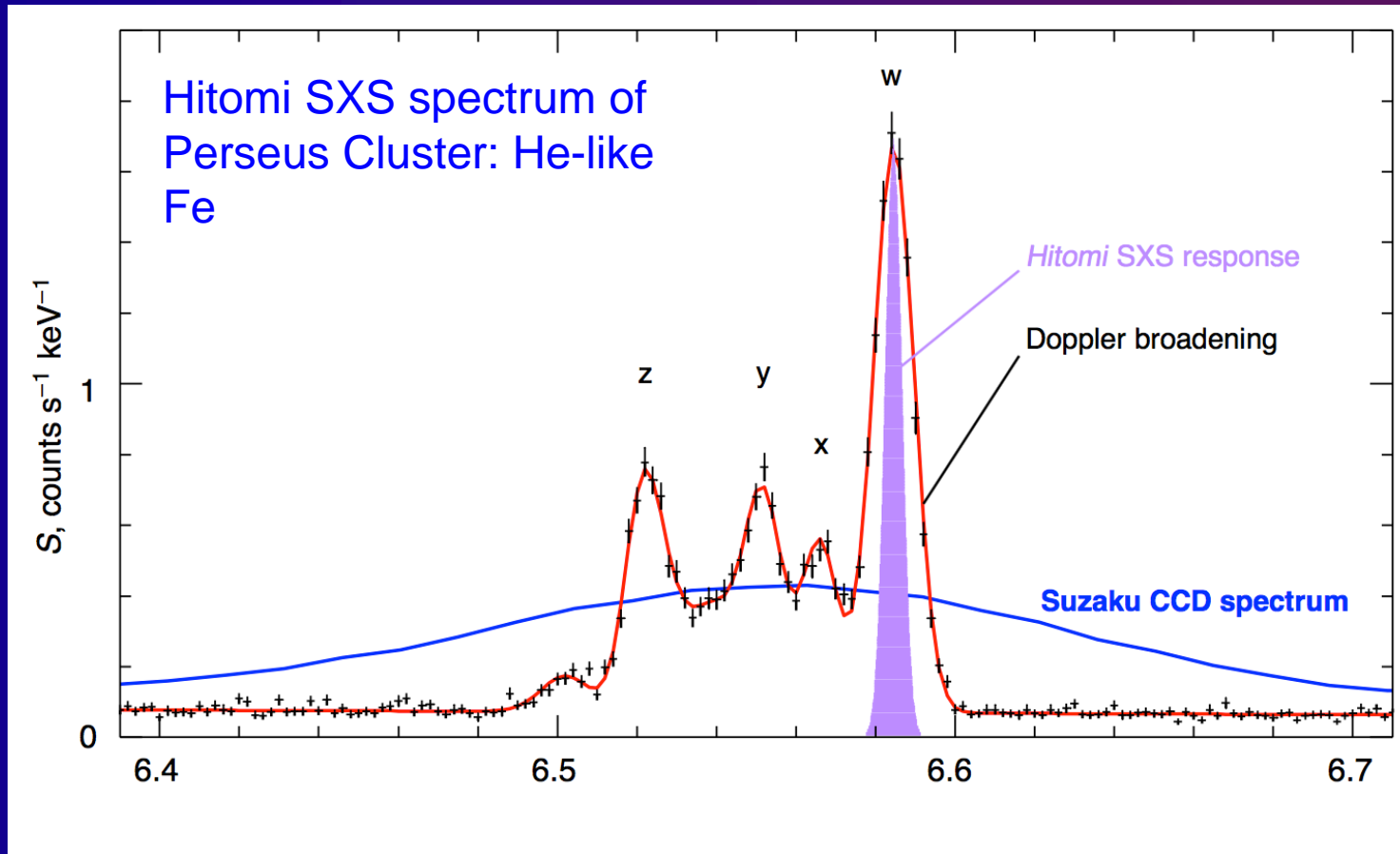


32 x 32 array



96 x 96 array

# Use for astrophysics – breakthrough performance of Hitomi/SXS



BLACK: Hitomi SXS data

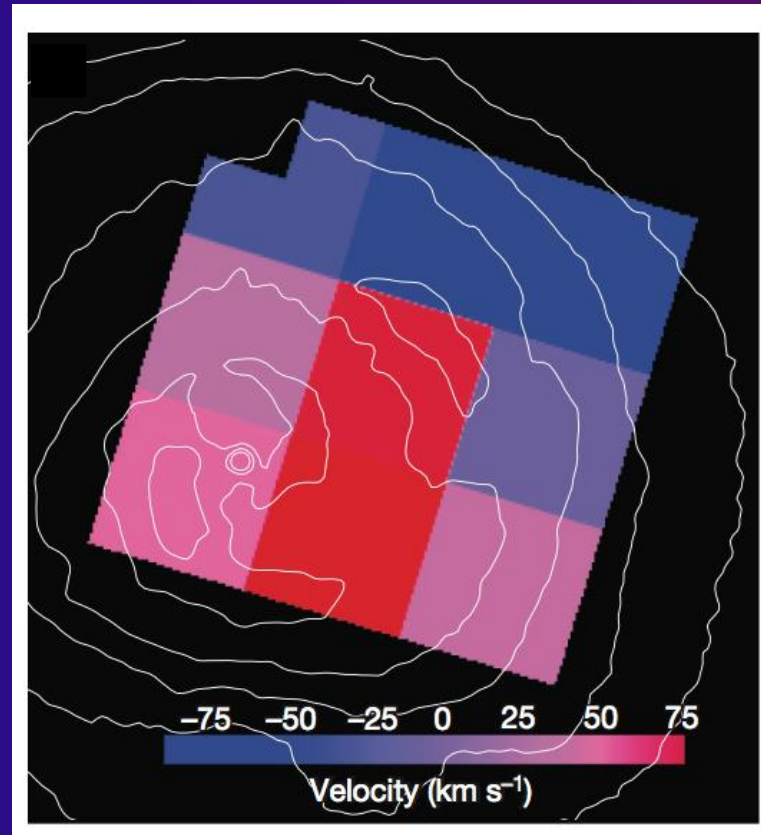
PURPLE: Hitomi SXS line response function

BLUE: Best previous spectrum (Suzaku CCD)

RED: Model

The line widths are much wider than the detector resolution, so the line shape actually tells us about the turbulence in the cluster gas. This turbulence, though easily measured, was surprisingly low.

# Use for astrophysics – breakthrough performance of Hitomi/SXS



Bulk velocity also seen to vary with position, and may be indicative of past mergers.

# The future

- The Hitomi satellite is no longer operational due to a problem, but work has started on a replacement.
- The European Space Agency is developing Athena, which will have a superconducting calorimeter array with nearly 4000 pixels.
- Other mission concepts are also being studied.
- The secrets of the HOT universe await the next cold probe!